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SUMMARY OF CORPS OF ENGINEERS METHODOLOGIES FOR MODELING WATER QUALITY OF ESTUARIES AND COASTAL EMBAYMENTS

by

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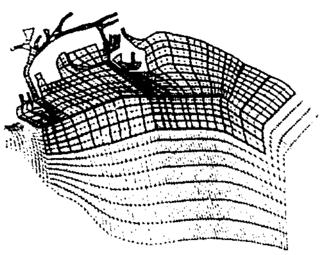
SAN PEDRO BAY
Water Quality Model Grid Overlay



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Corps of Engineers engineering activities that produce changes in estuaries and coastal embayments primarily do so by altering the circulation; alterations in the circulation can affect the concentration of water quality constituents; and changes in water quality constituent concentrations may adversely affect organisms. This report summarizes capabilities for modeling water quality impacts of those Corps activities that can alter circulation and transport in estuarine and marine systems.

Traditional waste load allocation models typically emphasize water quality kinetics while employing relatively coarse information on circulation. This report emphasizes the incorporation of accurate hydrodynamics either through coupling existing water quality models to hydrodynamic models or upgrading hydrodynamic models to include water quality.

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The proposed strategy for impact assessment is to first accurately investigate potential changes in circulation and transport. If no detectable changes occur, the chemical characteristics are assumed not to change. If, however, a transport change is detected, then changes in water quality constituent concentrations should be examined through a water quality modeling study. Available numerical models are presented, and a basic numerical modeling procedure is discussed.

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PREFACE

This report was prepared by the Environmental Laboratory (EL) of the US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, under the Environmental Impact Research Program (EIRP), Work Unit No. 31730, "Environmental Impacts of Modifying Estuarine Circulation and Transport Processes." The EIRP is sponsored by Headquarters, US Army Corps of Engineers (USACE). The USACE Technical Monitors were Dr. John Bushman, Dr. David Buelow, and Mr. Dave Mathis. Dr. Roger T. Saucier was EIRP Program Manager.

Mr. Ross W. Hall, Mr. Mark S. Dortch, and Ms. Sandra L. Bird, Water Quality Modeling Group (WQMG), prepared the report under the supervision of Mr. Dortch, Chief, WQMG; Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division; and Dr. John Harrison, Chief, EL. Ms. Jessica S. Ruff, Information Technology Laboratory, WES, edited the report.

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CONTENTS

SUMMARY OF CORPS OF ENGINEERS METHODOLOGIES FOR MODELING WATER QUALITY OF ESTUARIES AND COASTAL EMBAYMENTS

PART I: INTRODUCTION

Background

1. Estuaries and coastal embayments are important resources that are subject to environmental impacts due to Corps of Engineers (CE) activities. Compliance with state and Federal statutes, executive guidelines, and Corps regulations often requires prediction of the impacts of these activities. Environmental impacts of CE activities in estuarine and marine systems primarily involve water quality and biological resources. The focus of the work discussed herein is on water quality impacts.

2. Examples of CE activities that can impact water quality include: (a) disturbances during construction, (b) changes in project operations, such as freshwater inflow control, and (c) structural alterations, such as adding or modifying structures for flood control, storm surge protection, salinity control, and navigation (e.g., deepening and widening of navigation channels and construction of ports and harbors).

3. Disturbances during construction can cause short-term impacts, such as increased turbidity, spillage of contaminants, and local depression of dissolved oxygen (DO). Following termination of construction, these short-term water quality perturbations rapidly decline to background levels. The emphasis here is on long-term rather than short-term, temporary impacts. Resolving short-term, near-field impacts may require additional modeling capabilities that are not discussed herein.

4. The primary functions of the CE in estuarine/marine systems involve freshwater supply, storm and flood protection, and navigation. Through improved navigation or flood control, CE projects may enhance the opportunities for industrial and municipal development. Increased effluents resulting from industrial and municipal development can degrade water quality. On occasion, CE project managers might be involved in evaluating increased waste discharges, i.e., the indirect impacts of the CE activity. More likely, however, the manager must evaluate the direct impacts of the CE activities and consider

what impact changes in project operations or structural alterations will have on estuarine/marine water quality.

5. Both changes in project operations and structural alterations can cause long-term physical alterations, such as permanent changes in circulation. Physical alterations can alter the transport and concentration of water quality constituents, such as salinity and DO. Subsequently, changes in the water quality constituents may affect biological organisms. The cause-and-effect relationship between circulation, water quality, and biota changes suggests that environmental impact assessment for many CE activities can proceed by first evaluating circulation, then water quality constituents, and finally biota changes.

6. The Environmental Impact Research Program funded the work unit entitled "Environmental Impacts of Modifying Estuarine Circulation and Transport Processes." The emphasis of this work unit was on development of a capability to predict the impact of CE projects on estuarine/marine water quality. This report summarizes and provides guidance for the modeling methods identified and developed within this work unit.

Approach

7. A variety of water quality models have been available for some time to evaluate waste load allocation alternatives. Several of these models have been used for estuaries and coastal embayments (e.g., Feigner and Harris 1970; Hydroscience, Inc. 1971; Harleman et al. 1977; DiToro, Fitzpatrick, and Thomann 1983). These models focused on the impacts of waste discharges. Because CE activities often do not involve waste discharge, but rather physical alteration (operational or structural), it was questionable whether the modeling strategy used for waste load allocation studies would be adequate for addressing many CE projects. The traditional waste load allocation models emphasize water quality kinetics (sources/sinks and constituent transformations and interactions) while employing relatively coarse information on circulation. In most cases, the circulation used for the water quality is assumed to be adequate if the distribution of salinity can be adequately reproduced in the model.

8. To properly evaluate many of the CE impacts, accurate information on circulation and water quality kinetics must be included. Therefore, the

emphasis of this work unit was not on the development of new water quality models but rather the coupling of existing water quality models to hydrodynamic models used to address changes in circulation.

PART II: ESTUARINE SYSTEMS

9. Before the various estuarine/marine water quality modeling approaches can be presented in the next part, it is necessary to discuss basic concepts of estuarine circulation and the variety of conditions found in estuarine systems.

10. An estuary is a region where a river interacts with the sea. This condition indicates that at some point the river is influenced by tides. Tides influence water surface elevation, flow, and salinity. Estuarine systems can be extended to include coastal embayments and lagoons that exhibit estuarine characteristics. However, the freshwater flow of these systems may be harder to define because the tidal forcing may completely dominate circulation, and the freshwater source may be solely derived from local land runoff. The concurrent influence of tide, freshwater inflow, salinity gradient, and wind results in a complicated interaction of hydrodynamic, chemical, and biological processes. The following sections briefly summarize the various types of estuarine systems and the numerical models that can be used for each.

Estuarine System Classification

11. Numerous estuarine system classification schemes have been proposed. The classification schemes are based on both observed and derivable quantities of hydrography, estuarine circulation, stratification, and mixing types. Although no single estuarine classification scheme accurately distinguishes all estuarine systems, classification by mixing regime is commonly referenced and does provide a conceptualization of the influence of river inflow, density gradient, and tidal activity on estuarine transport. Estuaries may be classified as highly stratified, partially stratified, or well mixed.

Highly stratified estuary

12. If a river discharged into a nearly tideless sea, the less dense fresh water would flow outward over the seawater. An interface would exist between the overlying fresh water and underlying seawater. Shear stresses at the interface, resulting from the fresh water passing over the seawater, would push the interface downstream to a point where the slope of the interface would be sufficient to balance the shear. Interfacial shear results in an

exchange between the two layers. The exchange is due to the breaking of internal waves, which results in the net entrainment of water into the upper layer. This entrainment requires a net landward flow in the lower layer to counterbalance the increased flow in the upper layer. A net circulation results, with landward flow in the lower layer and seaward flow in the upper layer.

13. An estuary is highly stratified when the ratio of riverflow to tidal flow is relatively large and the width-to-depth ratio is relatively small. The interface between seawater and fresh water is reasonably well defined. An important consideration in highly stratified estuaries is that the vertical density differences significantly reduce the exchange of DO between the surface and bottom waters. The surface DO consumed by respiration is replaced through surface reaeration. However, replenishment of DO in the bottom waters through mixing with the oxygenated surface layers is inhibited by vertical stratification. Therefore, stratified conditions may result in depletion of DO in the bottom waters.

Partially stratified estuary

14. Increasing the tidal amplitude increases the exchange between the two layers due to increased interfacial shear and increased vertical velocities associated with the rising and falling tide. In a partially stratified estuary, a significant vertical salinity gradient remains, but the interface is less well defined and oscillates with tidal flow.

Well-mixed estuary

15. Further increase in the tidal amplitude results in even more exchange between the two water layers. A point is reached where this exchange is so intense that the stratified nature of the estuary is completely disrupted. In a well-mixed estuary, longitudinal salinity gradients exist, while vertical salinity gradients are slight. These estuaries are characterized by a tidal flow much larger than the riverflow. Velocities are unidirectional--landward during flood tide and seaward during ebb tide. In contrast to highly stratified estuaries where vertical stratification inhibits vertical mixing that may result in depletion of DO in bottom waters, well-mixed estuaries have a comparatively uninhibited exchange of aerated surface water and bottom water.

Other influences

16. The above analysis is very simplified. Only the effects of river inflow, density gradient, and tidal activity are considered. A particular estuary may temporally and spatially exhibit one or more of these mixing regimes; the transition from stratified to well mixed may occur with decreased riverflow or increased tidal velocities. Other influences contribute to the system's characteristics, such as local geometry/bathymetry and meteorology.

17. Tidal pumping is a term that refers to the interaction of the tidal wave and the bathymetry; the ebb flow path differs from the flood flow path in a consistent manner, causing a net circulation or "pumping" effect. One example of this circulation pattern occurs with the development of separate flood and ebb channels.

18. Meteorological effects range from water level variability due to surface pressure gradients to near-surface currents due to wind stress. Meteorological events can explain much of the flow variability in estuaries that are subtidal in frequency. In addition, if the estuary is large enough, wind stresses can generate residual circulation of considerable magnitude.

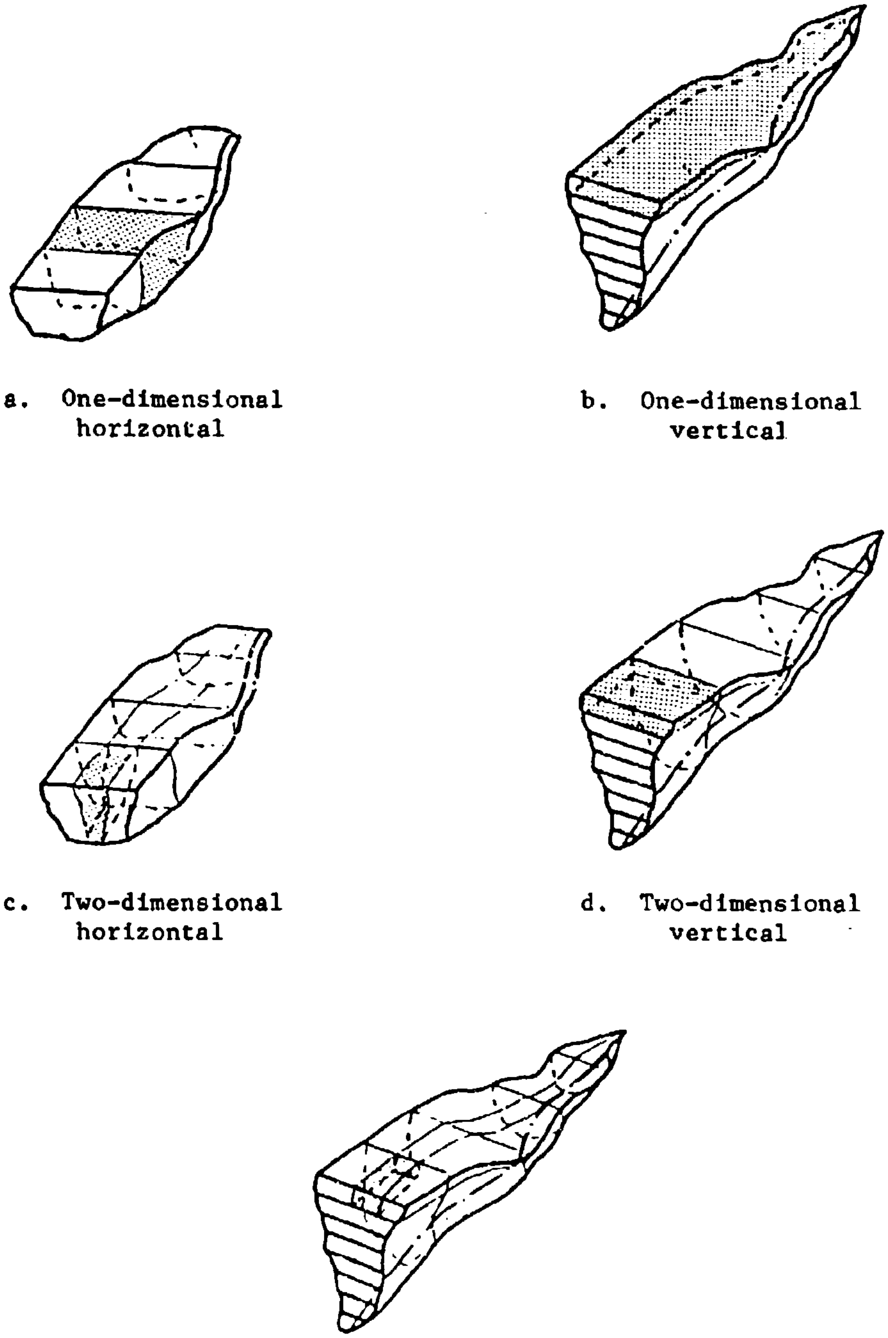
19. Numerous residential canals and marinas have been constructed along the coast of the United States. A canal is a long, narrow waterway that is used primarily for access to residencies with docking facilities. In contrast, marinas are primarily used for boat docking; their width is on the same order of magnitude as their length.

20. The flows in residential canal systems are complex, time-varying interactions of forcing due to tide, wind, density-induced currents, and secondary currents due to hydrographic features such as bends and sills. In marinas, wind tends to be relatively unimportant, except in driving the adjacent water body, because fetch lengths are small and there is masking due to trees and houses. However, adjacent along-shore currents induce mixing within the marina through shear. Density-induced currents are small because little fresh water enters these systems. Unfortunately, many canals and marinas flush poorly, have poor water quality, and are filling with silt (Walton 1983).

Models for Estuarine Systems

21. Although estuaries are three-dimensional (3-D), the complexity of mathematical models of them is often reduced by assuming that variations in one or more dimensions are small enough to be ignored or averaged (see Figure 1). For example, a long, narrow, and vertically well-mixed water body may be represented by a one-dimensional (1-D) model consisting of a series of segments averaged over the cross section. Where pronounced vertical stratification occurs in a narrow estuary, a laterally averaged two-dimensional model (2-D) will be needed. If marked lateral heterogeneities occur in a vertically well-mixed estuary, then a depth-averaged 2-D model should be used. If significant lateral heterogeneities are accompanied by pronounced stratification, a 3-D model may be required. In general, 2-D models are substantially more expensive to apply than 1-D models, and 3-D models are much more expensive than 2-D models. Hence, where a simpler model will produce satisfactory results, it should be used.

22. For flow-through canals and marinas where the tide dominates, 1-D longitudinal models, such as link-node models, may be adequate. Modeling wind effects and density-induced currents requires, at the minimum, a 2-D laterally averaged model. Modeling shear-induced circulation in harbors and marinas requires at the minimum a 2-D vertically averaged model (Walton 1983).



a. One-dimensional horizontal

b. One-dimensional vertical

c. Two-dimensional horizontal

d. Two-dimensional vertical

e. Three-dimensional

Figure 1. Comparison of model dimensions

PART III: NUMERICAL MODELING APPROACHES

Basic Strategy

23. The proposed modeling strategy is to allow a progression of evaluation methodologies. As a first step, the modeler should investigate changes in circulation and transport resulting from the CE activity (operational or structural modification). If no detectable changes in circulation/transport occur, then the chemical characteristics may be assumed not to change. If, however, a significant change in circulation/transport is detected, an assessment of the degree of water quality change should be made.

24. Changes in circulation can be evaluated by examining the velocity fields for preproject and postproject conditions. Minor changes in the velocity field can translate into significant changes in transport when considered over a long period of time (e.g., a week, month, season). Changes in transport can be detected by simulating salinity or passive dissolved substances, such as an arbitrary conservative tracer (i.e., dye), and comparing concentrations (or their differences) in time and space for preproject and postproject conditions. By examining the tracer concentrations with time, the flushing characteristics can be evaluated. As the rate of flushing decreases, a parcel of water (and its tracer concentration) remains for a longer period of time in a particular location. Another way to view flushing characteristics is to compute the age of the water throughout the model domain. This can be easily done by transporting an arbitrary constituent (e.g., "age") that has a source term equal to the model time step. An increase in the age indicates a decrease in the flushing rate, prolonging the period of time that oxygen-demanding substances would exert their influence on the DO concentration. Generally, it may be concluded that an increase in age or a decrease in flushing rate can intensify existing water quality problems, and more detailed water quality analyses are required.

25. Many hydrodynamic models have the capability to transport salinity or other passive constituents; thus, it may be possible to examine the transport along with the circulation. However, if long-term transport simulations are to be performed, improvising may be necessary so that the simulation costs are not excessive. A discussion of this problem and methods for improvising are discussed in the remainder of this section and in the next section.

26. The numerical model study of Lower Green Bay by Swain and Bird (1987) is a good example of the use of hydrodynamic/transport modeling to examine the impact of a proposed CE activity. The US Army Engineer District (USAED), Detroit, was proposing a major expansion of an existing offshore confined disposal facility (CDF) for dredged material. There was concern that the expansion might hinder circulation and mixing of pollutants in the Fox River, which discharges into Lower Green Bay.

27. The 2-D vertically integrated hydrodynamic/transport model WIFM-SAL (Schmalz 1985) was used for the study. Lower Green Bay is wide and shallow; thus, a 2-D vertically integrated model was justified. A periodic steady-state flow condition was simulated by the hydrodynamic model by imposing a constant river discharge and a repeating seiche head boundary condition at the open-water boundary. This flow field was saved and subsequently used to drive the transport simulations; the WIFM-SAL transport code was executed independently of the hydrodynamic calculations. The decoupling of transport calculations eliminated repetition of hydrodynamic calculations, resulting in significant computational savings. The transport simulations were done with the same grid resolution and time step; however, a subset of the hydrodynamic grid was employed to reduce computational expense and size of the hydrodynamic data set for the transport simulations. A passive constituent was simulated for pre- and post-CDF expansion to provide an assessment of the impact on circulation, transport, and water quality.

28. One of the greatest difficulties with using the transport of conservative (passive) constituents to detect potential water quality impacts is deciding what constitutes a significant change. This was the case in the Lower Green Bay study; the change in average concentration of the conservative constituent within the critical area at the mouth of the Fox River was less than 1 percent. This magnitude of change is within the accuracy limitation of the waste load allocation model that was previously used for this system. However, even though these changes were small, concerns were expressed over the consideration of averaged tracer quantities, and direct calculation of DO changes would have been less controversial. Only when changes are very small can water quality impacts be safely inferred on the basis of a conservative constituent.

29. If the circulation and transport simulations indicate significant changes in the system, water quality model simulations should be conducted to

determine the extent of impact. Water quality simulation models include constituents such as temperature, salinity, bacteria, DO, biochemical oxygen demand (BOD), algae, nutrients, and possibly toxic substances. These constituents (with the exception of salinity) are not conservative, which means that their concentrations can change through means other than transport, such as response to external forces (e.g., meteorology), reaction with each other, growth, decay, adsorption/desorption, and settling. Additionally, water quality models include arbitrary conservative constituents that can be used to evaluate transport/flushing characteristics. While conservative tracer analyses are valuable, they do not indicate the actual water quality. Dissolved oxygen and other water quality constituents can be used as a measure of the "health" of aquatic systems by comparison with published standards and criteria. More importantly, water quality concentrations reflect the interrelationship of the circulation, chemistry, and biology of the system.

30. After assessing the degree of water quality change, aquatic biologists could attempt to interpret the impact of predicted water quality changes on aquatic biological resources. The scope of this work unit did not permit the evaluation or development of techniques for addressing impact on the aquatic biological resources. Additionally, the scope did not permit the evaluation or development of techniques for addressing questions pertaining to specific nonconventional transport issues, such as larval fish transport and fate of toxic substances. However, larval fish and toxic substance transport are logical extensions of the developments discussed here.

Coupling of Hydrodynamics and Water Quality

31. Hydrodynamic models calculate flows that are subsequently used by water quality models to describe the movement of water quality constituents. Numerical models of lower dimensionality (e.g., 1-D and 2-D laterally averaged models) carry sufficiently low computational burden to allow hydrodynamic and water quality simulations within the same code (or in a companion code) using the same grid and time step. The use of the same grid and time step is termed direct linkage, or coupling, of water quality to the hydrodynamics. Direct coupling is rather straightforward. For models of higher dimensionality and greater computational expense (i.e., 2-D vertically averaged and 3-D), direct coupling may be cost prohibitive, and it may be necessary to indirectly couple

the water quality to the hydrodynamic solution. Indirect coupling consists of spatially and/or temporally averaging the hydrodynamic model output, storing this output, and subsequently using it as input to drive the water quality model. Indirect coupling usually involves implementing a water quality code that is separate and distinctly different from the hydrodynamic model. An intermediate program may also be required to facilitate coupling of the two models. Various implications and considerations of direct and indirect linkages are discussed in this and the next section.

32. Directly coupled models have the following advantages: (a) they can be applied more easily because intermediate processing between the hydrodynamic and water quality computations is not needed, (b) hydrodynamic and water quality variables directly correspond in time and space since the same spatial and temporal scales are used, and (c) usually, the same code can be used to examine circulation, transport, and water quality. The disadvantage of direct coupling is that the computational costs can be prohibitive, depending on the application.

33. The temporal and spatial resolution necessary for many hydrodynamic model applications may be greater than required for water quality and can lead to unacceptable computer costs when simulating multiple constituents for long-term events. The current trend in hydrodynamic modeling is toward development of 3-D models with increased spatial and temporal resolution to resolve important scales and to minimize the need for parameterization. As a result, hydrodynamic models often have time steps on the order of minutes. In contrast, the chemical and biological equations of water quality models have characteristic time scales determined by the kinetic rate coefficients. These time scales are usually on the order of days. Often the phenomena of interest, such as depletion of DO and excessive plant growth, occur on time scales of days to months. Thus, it is not necessary to use the same time scale in the water quality simulations that was used in the hydrodynamics. Similarly, hydrodynamic models may use a rather fine grid in some applications to resolve the flow field near special geometric features such as inlets, jetties, and harbors. The degree of spatial resolution may be necessary for preservation of the transport properties for the water quality model, but may be more than necessary to model the kinetic processes. Therefore, it may be desirable to perform some temporal and spatial averaging of the hydrodynamic output to

reduce computational cost while ensuring that the basic transport properties are preserved.

34. The only advantage of indirect coupling is the reduction of computational costs; indirect coupling can reduce costs by orders of magnitude. Multidimensional, multiconstituent, time-varying, long-term water quality simulations may be economically feasible only if an indirect coupling approach is used. The disadvantages of indirect coupling are antitheses of the advantages of direct coupling. Indirect coupling requires intermediate processing, hydrodynamic and water quality variables do not directly correspond in space and time, and the water quality and hydrodynamic code may possess few structural similarities such as computational cell identification. Additionally, it may be difficult to preserve the transport properties, depending on the degree of temporal and spatial averaging.

35. Investigations by Bird and Hall (1988) were conducted to examine the effects of spatial and temporal averaging. In these studies, a multiple-box (integrated compartment, i.e., the mass balance equation is integrated over a control volume or box) model was used for the transport code. This method was used because it lends itself to coupling to a variety of hydrodynamic models with different types of grids and solution methods, such as finite difference, finite element, and boundary-fitted coordinates. The basic conclusions and recommendations of these studies were:

a. The box model is a computationally feasible approach for long-term multidimensional water quality modeling that provides a flexible framework to interface with a variety of hydrodynamic models in 1-, 2-, 3-, or mixed-dimensional applications.

b. The box model has a dispersive-type solution scheme, and the inclusion of a dispersion-controlled scheme in a box model format would significantly increase the accuracy and utility of this approach. Incorporation of the QUICKEST solution scheme (Hall and Chapman 1985, Ray Chapman and Associates 1988) in a box model format for a water quality application to Los Angeles/Long Beach Harbor is currently under way which will provide a significant improvement in box modeling technology.

c. Long-term, multidimensional, intertidally averaged box model simulations require the development of methods to calculate residual currents and dispersion coefficients.

Available Numerical Models

36. Because of the variety of circulation conditions found in estuaries and coastal embayments, it is necessary to have a variety of models available. A general 3-D model can be used for a variety of systems, but the cost of application is usually prohibitive. Therefore, the appropriate model may be 1-, 2-, or 3-D depending on the requirements of the study and the characteristics of the system.

37. Available 1-, 2-, and 3-D models are briefly described below. Some of these models were studied and improved during this work unit. Others are identified for potential use.

One-dimensional models

38. Steady-flow, 1-D models are usually used for waste load studies of well-mixed, river-dominated estuaries. These models use tidally averaged flows, and dispersion is calibrated to match salinity. A simplified model of this type may be adequate to evaluate various levels of river discharge on water quality, but a more sophisticated flow model would be required to evaluate complex physical alterations such as changes in channel networks.

39. CE-QUAL-RIV1 is a dynamic (time-varying flow and water quality), one-dimensional (longitudinal) water quality model originally developed for highly transient flows in streams (Environmental Laboratory, in preparation). Enhancements made to CE-QUAL-RIV1 in this work unit increase the model's flexibility to allow application to well-mixed estuaries or canals. These enhancements include provision for tidal boundary conditions, reversing flows, and branched/looped channel systems.

40. The hydrodynamic and water quality codes are separate but use the same spatial and temporal grid. The hydrodynamic code uses the four-point implicit Newton-Raphson procedure (Amein and Fang 1970a,b) to solve the nonlinear St. Venant equations. The water quality code uses the explicit two-point, fourth-order-accurate Holly-Preissmann scheme (Holly and Preissmann 1977), which preserves advective transport accuracy with little numerical diffusion. The code allows simulation of dendritic systems with in-stream hydraulic control structures.

41. Simulated water quality constituents include temperature, DO, carbonaceous BOD, organic nitrogen, ammonia nitrogen, nitrate nitrogen, orthophosphate phosphorus, coliform bacteria, dissolved iron, and dissolved

manganese. The interactions with algae and aquatic plants are presently included as processes rather than through state variables. Conservative substances can also be included.

42. QUAL-2E (Brown and Barnwell 1985) is another 1-D stream model that may be useful for well-mixed, riverine-estuarine conditions. This model, developed and maintained by the US Environmental Protection Agency (USEPA) assumes steady flow; thus, tidally averaged flow conditions would have to be used. The greatest advantages of this model are the ease of application and the fairly comprehensive algal/nutrient interactions. This model has been applied to estuarine conditions.

Two-dimensional
laterally averaged models

43. CE-QUAL-W2 is a two-dimensional laterally averaged hydrodynamic and water quality model developed for reservoirs and estuaries (Environmental Laboratory and Hydraulics Laboratory 1986). Features include the capability to handle a system composed of several branches or closed loops. The hydrodynamics are influenced by the density stratification resulting from salinity, temperature, and suspended solids. Several enhancements were made to CE-QUAL-W2 throughout this work unit.

44. This model is not as computationally expensive to apply as most 2-D and 3-D models. Hydrodynamic and water quality simulations have been conducted for prototype periods of months (Hall 1987) with acceptable computer time requirements. The computational requirements for hydrodynamic and water quality (all constituents) simulations are about equal. At the time of this writing, the water quality and hydrodynamic computations must be conducted concurrently in the same run. However, there are plans to decouple these computations to allow indirect linkage and thus reduce computational expense for water quality modeling.

45. The water quality coding in CE-QUAL-W2 is arranged into hierarchical levels of complexity, allowing the user to select the level of water quality detail desired for a particular study. The first level of complexity deals with noninteractive (without feedback) constituents (e.g., conservative tracer, temperature, salinity, suspended solids, and coliform bacteria). The second level allows DO-BOD or DO-BOD-nutrient-phytoplankton dynamics. The third level includes, in addition to the variables in the first two levels, pH and carbonate species.

Two-dimensional depth-averaged models

46. WIFM-SAL (Schmalz 1985) may be used in the analysis of water quality problems in shallow estuaries and embayments that are considered vertically well mixed. The model is two-dimensional in the horizontal and generates time-varying water surface elevations, velocities, and constituent fields over a space-staggered grid. Results computed on a global grid may be employed as boundary conditions on a more spatially limited refined grid concentrated around the area of interest. The user may select either of two distinct transport schemes. Scheme 1 is a flux-corrected transport scheme capable of resolving sharp fronts without oscillation. Scheme 2 is a three-time level scheme directly compatible with the three-time level hydrodynamics.

47. In WIFM-SAL, the hydrodynamic and transport codes are imbedded, and a direct linkage is employed. However, the transport computations can be done following hydrodynamic solution by storing and reading in the hydrodynamic information. A variant, WIFM-TRANS, uses indirectly coupled codes with the same spatial grid but with optional time averaging. Although WIFM-SAL and WIFM-TRANS provide constituent transport capability, the codes do not contain the kinetics associated with water quality modeling. This capability could be implemented for specific applications.

48. The TABS-2 system uses depth-averaged finite element models to predict hydrodynamics, sedimentation, and constituent transport (Thomas and McAnally 1985). The system consists of more than 40 computer programs to perform modeling and related tasks. The programs RMA-2V, STUDH, and RMA-4 calculate flows, sedimentation, and constituent transport, respectively, for 2-D depth-integrated water bodies. Other programs perform digitizing, mesh generation, data management, graphics display, output analysis, and model interfacing tasks.

49. DYNTRAN (Moore and Walton 1984) is a quasi-2-D, link/node type model wherein the prototype system is divided into a system of junctions (nodes) where geometric properties of volumes and surface area are joined by links or hydraulic pathways along which flow moves from one nodal volume to another. Multiple links may come into any junction, allowing the formation of a 2-D (horizontal) grid. However, 1-D flow is assumed through each link. This model is most appropriate for a channelized system where the principal flow path is well defined. For applications in open embayments, one of the fully 2-D models described above would be more appropriate. DYNTRAN includes

mass transport of salt and a second constituent, which may be conservative or nonconservative. At the time of this writing, this model was being applied by the US Army Engineer Waterways Experiment Station (WES) to the Bolsa Chica Bay System (canals and marinas) on the California coast for the USAED, Los Angeles.

Three-dimensional models

50. The CE has sponsored the development of two 3-D hydrodynamic models. The first, RMA-10, uses the finite element method of solution (King 1982); the second, CELC3D, uses the finite difference method of solution (Sheng 1983). Both models were developed similarly to the depth-averaged models RMA-2V and WIFM. The latest version of CELC3D is referred to as CH3D and uses boundary-fitted coordinates to map the grid to the plan geometry. These models have constituent transport capability but do not include specific source/sink and reaction terms for water quality.

Multiple-box model

51. The multiple-box model method consists of driving a finite segment (also referred to as integrated compartment or box) water quality model with output from a hydrodynamic model. A general multidimensional hydrodynamic model is not included in the code. Therefore, hydrodynamic information is usually generated by an available hydrodynamic model and provided as input. Usually, the hydrodynamic model output is averaged over time and (sometimes) space, resulting in indirect coupling. The box model grid is an overlay of the hydrodynamic model grid, but each box may encompass several hydrodynamic model cells. The number of box model segments, the time step, and dispersion coefficients are adjusted to ensure transport with the box model adequately reproduces that of the finer scale hydrodynamic/transport model. The USEPA's multiple-box model WASP (Water Quality Analysis Simulation Program) (Ambrose, Vandergrift, and Wool 1986) was selected as the framework for a versatile water quality model that could be interfaced with any hydrodynamic model. The WASP code may be applied in 1-, 2-, or 3-D configurations and contains a variety of water quality algorithms that the user may select, including toxic substances.

52. Methods for indirect coupling of hydrodynamic output to WASP were investigated (see section, Coupling of Hydrodynamics and Water Quality) using the CE-QUAL-W2 and WIFM-SAL hydrodynamic/transport models (Bird and Hall 1988). Transport computation times were reduced by several orders of

magnitude through this indirect coupling. A recent improvement to the WASP solution scheme was implementation of a higher order advection scheme to reduce numerical diffusion (Ray Chapman and Associates 1988).

53. The box model approach will be used to conduct long-term water quality model simulations for most 2-D vertically integrated and 3-D applications. Examples of the use of this methodology include the 3-D water quality model studies currently under way by the WES on the Los Angeles-Long Beach Harbor and Chesapeake Bay.

Numerical Modeling Procedure

54. The highly complex and unique nature of estuarine systems precludes a simple analysis of water quality impacts. Thus, a numerical model is often required. The basic procedure is the same for all numerical modeling studies. A flowchart indicating the general steps for conducting a numerical water quality modeling study is presented as Figure 2. The steps in the procedure are discussed in the following paragraphs.

Problem identification

55. Before modeling objectives are determined, the problems, questions, and issues to be addressed must be identified. How the answers will be used should also be identified. Problem identification will often reveal if the problem is amenable to numerical model analysis.

Modeling objective

56. In consultation with all interested parties, a modeling objective must be determined that addresses the problems/questions/issues that were identified. Without a clear and concise modeling objective, any modeling effort faces a high probability of failure. The modeling objectives should help define the desired resolution limits, constituents of interest, and the expected output.

Study design and model selection

57. The study design is used to plot how the objectives will be met and addresses model selection, data compilation, data analysis, model testing, model simulations, and output interpretation. The study design also includes study milestones, resource allocations, and technology transfer. The depth and detail of the model study should be commensurate with the other study

elements in the current stage of project planning or engineering, and consistent with the overall project scope and funding.

58. Model selection is the most important part of the modeling procedure. Selection of an inappropriate model can result in failure to meet the study objectives. For estuaries and coastal embayments, model selection depends primarily on the characteristics of the system (see Part II). However, the issues to be resolved and the objectives of the study should also be considered to ensure success.

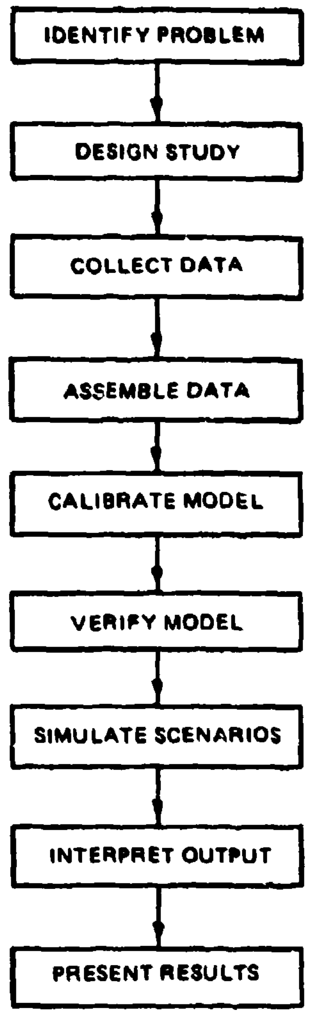


Figure 2. General steps for conducting a numerical water quality modeling study

Data assessment and collection

59. Determining what field data exist and what data are to be collected is necessary to drive, calibrate, and verify the model. The resolution of the model is only as good as the data used to drive the model. For example, water quality data collected at monthly intervals could be used to resolve phenomena at temporal scales of seasons to years but would be inadequate to resolve phenomena at temporal scales less than a month. Also, appropriate field observations are required to properly calibrate and verify the model. The subject of appropriate field observations is involved and depends on specific study objectives and the modeling approach, and cannot be discussed in detail in this report. The reader is referred to Beck (1983a,b) and Ditmars et al. (1987)

Data assembly

60. The data required generally consist of geometric schematization, initial and boundary conditions, hydraulic properties, and biological and chemical parameters. Calibration and verification data are not used in the execution of the simulations but are required for model calibration and verification.

Calibration

61. Calibration consists of comparing predictions with historical field data to estimate model parameters. Although estimates of model parameters may be available from published literature, determination of the "best" values for a particular application often requires subjective adjustment of the parameters until an "adequate fit" of the simulated data is obtained.

Verification

62. Verification consists of application of the model to a second, independent data set to determine if the model will yield reliable predictions without additional model adjustments. Model verification reduces the risks associated with the model's use. More recently, model verification has also been referred to as model confirmation (Chapra and Reckhow 1983), with the latter involving statistical tests and error analyses to confirm a model's accuracy.

Scenario simulations

63. The calibrated and verified model may be used for scenario simulations. Scenarios could represent existing conditions and proposed management or design alternatives. Simulations could also be conducted to evaluate the sensitivity of the system to various inputs.

Output interpretation

64. Model simulations can produce an overwhelming quantity of output. Statistical and graphical tools enable data summarization and aid in interpretation. An amount of time equivalent to that required for data assembly is generally required for output interpretation.

Presentation of results

65. The results should be presented in a format appropriate for the intended audience. Presentation of large volumes of data is generally undesirable, but provision should be made for long-term storage and retrieval. Graphical displays are effective for demonstrating major conclusions.

PART IV: SUMMARY AND RECOMMENDATIONS

66. Corps of Engineer activities that can impact water quality include (a) disturbances caused by construction, (b) changes in project operation, such as freshwater inflow control, and (c) structural changes, such as adding or modifying structures for flood control, storm surge protection, salinity control, and navigation (e.g., deepening and widening navigation channels and construction in support of ports and harbors). Activities (b) and (c) are of interest here. These activities can cause long-term physical alterations, such as permanent changes in circulation. Physical alterations can alter the transport and concentration of water quality constituents such as salinity and dissolved oxygen. These changes in the water quality constituents may affect biological organisms. The cause-and-effect relationship of circulation, water quality, and biota changes suggests that environmental impact assessment for many CE activities can proceed by first evaluating circulation, then water quality constituents, and finally biotic changes. This report summarizes capabilities for modeling water quality impacts of those CE activities that can alter circulation and transport in estuarine/marine systems.

67. The traditional waste load allocation models emphasize water quality kinetics while employing relatively coarse information on circulation. To properly evaluate many of the CE impacts, accurate information on circulation and water quality kinetics must be used. Therefore, the emphasis of this work was not on the development of new water quality models, but rather the coupling of existing water quality models to hydrodynamic models or the upgrading of hydrodynamic models to include water quality transport.

68. The proposed strategy for impact assessment is to first accurately investigate potential changes in circulation and transport. If no detectable changes occur, then it is assumed that the chemical characteristics will not change. If, however, a change is indicated, possible changes in water quality constituent concentrations should be examined through the appropriate water quality modeling study. The water quality model must be able to take into account the changes in circulation and transport. A variety of water quality models are available to address the various types of estuaries and coastal embayments. These models are briefly summarized in Part III.

69. The greatest difficulty in water quality modeling of estuarine/marine systems is that multidimensional numerical models are often required,

which can result in great computational expense when conducting long-term water quality simulations. During the effort reported here, methods for reducing this expense were examined through the use of indirect coupling of hydrodynamic and water quality models. Although progress has been made in the area of indirect coupling, coupling strategies should be extended to ensure preservation of the transport characteristics in the water quality model for a broader spectrum of model applications, such as the use of intertidal hydrodynamics to drive the water quality model. However, with further advances in computer speed, the need for indirect coupling will diminish.

70. Future efforts in estuarine/marine water quality model development should be directed toward advancing the capability to simulate the diagenesis of bottom sediments. In some systems, such as Chesapeake Bay, the bottom sediments are a significant factor impacting the water quality (HydroQual 1987). Years of excessive nutrient loadings have created this condition. It is not possible to fully evaluate nutrient control strategies and future water quality conditions without the capability to predict changes in sediment quality and fluxes. Likewise, a truly predictive water quality model must be able to simulate the degradation of the sediments resulting from changes in loadings or circulation. Water quality models that simulate the interaction of the sediments and the water column may require long-term simulations since the response time of sediments can be on the order of years.

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